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Soil Total Carbon and Crop Yield Affected by Crop Rotation and Cultural Practice

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Abstract

Stacked crop rotations and improved cultural practices have been used to control pests, but their impact on soil total carbon (STC) (soil organic carbon [SOC] + soil inorganic carbon [SIC]) and crop yield are lacking. We evaluated the effects of stacked vs. alternate-year rotations and cultural practices on STC at the 0- to 125-cm depth and annualized crop yields from 2005 to 2011 in the northern Great Plains. Stacked rotations were durum (*Triticum turgidum* L.)–durum–canola (*Brassica napus* L.)–pea (*Pisum sativum* L.) (D–D–C–P) and durum–durum–flax (*Linum usitatissimum* L.)–pea (D–D–F–P). Alternate-year rotations were durum–canola–durum–pea (D–C–D–P) and durum–flax–durum–pea (D–F–D–P). A continuous durum (CD) was used as a reference. Cultural practices were traditional (conventional till, recommended seed rate, broadcast N fertilization, and reduced stubble height) and ecological (no-till, increased seed rate, banded N fertilization, and increased stubble height) treatments. Annualized crop biomass residue returned to the soil and grain yield were greater with D–C–D–P and D–D–C–P than D–D–F–P and greater with the ecological than the traditional practice. The STC concentration increased with depth and was greater with CD and D–C–D–P than D–D–C–P and D–D–F–P in traditional and ecological practices at 20 to 50 cm. At 50 to 88 cm, STC concentration was greater with D–F–D–P than D–D–F–P in the traditional practice. At 0 to 125 cm, STC content was lower with D-D-F-P than other crop rotations. Stacked rotations, especially D–D–F–P, reduced soil C storage and crop yields compared with alternate-year rotations. For enhancing soil C storage and crop yields, alternate-year crop rotations are recommended.

Disciplines

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ABSTRACT

Stacked crop rotations and improved cultural practices have been used to control pests, but their impact on soil total carbon (STC) (soil organic carbon [SOC] + soil inorganic carbon [SIC]) and crop yield are lacking. We evaluated the effects of stacked vs. alternate-year rotations and cultural practices on STC at the 0- to 125-cm depth and annualized crop yields from 2005 to 2011 in the northern Great Plains. Stacked rotations were durum (*Triticum turgidum* L.)–durum–canola (*Brassica napus* L.)–pea (*Pisum sativum* L.) (D–D–C–P) and durum–durum–flax (*Linum usitatissimum* L.)–pea (D–D–F–P). Alternate-year rotations were durum–canola–durum–pea (D–C–D–P) and durum–flax–durum–pea (D–F–D–P). A continuous durum (CD) was used as a reference. Cultural practices were traditional (conventional till, recommended seed rate, broadcast N fertilization, and reduced stubble height) and ecological (no-till, increased seed rate, banded N fertilization, and increased stubble height) treatments. Annualized crop biomass residue returned to the soil and grain yield were greater with D–C–D–P and D–D–C–P than D–D–F–P and greater with the ecological than the traditional practice. The STC concentration increased with depth and was greater with CD and D–C–D–P than D–D–C–P and D–D–F–P in traditional and ecological practices at 20 to 50 cm. At 50 to 88 cm, STC concentration was greater with D–F–D–P than D–D–F–P in the traditional practice. At 0 to 125 cm, STC content was lower with D-D-F-P than other crop rotations. Stacked rotations, especially D–D–F–P, reduced soil C storage and crop yields compared with alternate-year rotations. For enhancing soil C storage and crop yields, alternate-year crop rotations are recommended.

Core Ideas

- Stacked crop rotation and improved cultural practice can control pests.
- The effects of such management practices on soil total carbon is lacking.
- Effects of crop rotation and cultural practice on STC and crop yield were evaluated.
- Crop yield and STC at several depths were lower in stacked than other rotations.
- Alternate-year rotation may enhance crop yield and STC compared to other rotations.

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Agricultural practices can emit significant level of CO_2 that contributes to global warming (Halvorson et al., 2002; Mosier et al., 2006; Sainju et al., 2014). Interests in using novel management practices, such as no-till, diversified crop rotation, cover crops, and increased cropping intensity, to sequester C in the soil and reduce atmospheric CO_2 concentration are increasing (Gan et al., 2012; Sainju et al., 2015a; Plaza-Bonilla et al., 2016). Additional benefits of C sequestration include enhanced soil health and quality, increased crop yields (Bauer and Black, 1994; Sainju, 2014), and additional income to producers from C credit markets (Paustian et al., 1997; Lal et al., 1999).

Traditional farming practices, such as conventional till with spring wheat (*Triticum aestivum* L.) –fallow, for the last several decades have reduced SOC by 30 to 50% from the original level in the northern Great Plains (Peterson et al., 1998, Sainju et al., 2015a). While tillage and fallow increase the mineralization of SOC (Bowman et al., 1999; Schomberg and Jones, 1999), fallow also reduces the amount of plant residue returned to the soil and C input, thereby negatively affecting SOC storage (Black and Tanaka, 1997; West and Post, 2002; Sainju et al., 2015a). With the adoption of no-till or reduced-till and continuous cropping systems leading to increased crop yields, the area under fallow has been steadily decreasing in recent years in the northern Great Plains (Campbell et al., 2002; Gan et al., 2011).

Besides SOC, management practices can also influence SIC in dryland cropping systems. Various researchers (Cihacek and Ulmer, 2002; Monger, 2002; Sainju et al., 2015a) have reported that conventional tillage can increase SIC compared with no-tillage. Incorporation of residue into the soil in the conventional tillage system increases microbial activity which can increase the formation of $CaCO_3$, thereby increasing SIC (Monger, 2002). Increased N fertilizer rates and continuous application of NH_4–based N fertilizers can increase soil acidity which solubilize SIC in the surface soil and translocate it to the subsoil layers (Mikhailova and Post, 2006). Limited precipitation and upward capillary movement of groundwater rich in soluble Ca and Mg during dry periods also increases SIC in dryland compared with irrigated cropping systems (Monger,

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Abbreviations: CD, continuous durum; D–C–D–P, durum–canola–durum–pea; D–D–C–P, durum–durum–canola–pea; D–D–F–P, durum–durum–flax–pea; D–F–D–P, durum–flax–durum–pea; SIC, soil inorganic carbon; SOC, soil organic carbon; STC, soil total carbon.

2002; Cihacek and Ulmer, 2002; Sainju et al., 2015a). Because of the presence of large quantity of SIC, especially in the subsoil layers, in dryland cropping systems of the semiarid and arid regions (Sainju et al., 2015a) and management practices can influence both SOC and SIC, we examined the effect of crop rotation and cultural practices on STC that comprises both SOC and SIC. Our view was that if these practices can significantly influence STC, then changes in STC may be used as an indicator of total C sequestration in the soil in response to management practices. Analyzing soil samples only for STC will reduce the cost of analysis for producers, especially in arid and semiarid regions, compared with double analysis of samples for SOC and SIC for measuring soil C sequestration.

Crop diversification that includes legumes and oilseed crops in rotation with cereals can increase crop yields by efficiently utilizing water and nutrients compared with monocropping in water-limited dryland cropping systems (Miller et al., 2002; Gan et al., 2011). An example is the inclusion of pea which requires less water than spring wheat and barley (*Hordeum vulgare* L.) and reduces N fertilization rate for succeeding crops by supplying N from pea residue (Miller et al., 2002; Sainju et al., 2014). Additional benefits of crop diversification include effective control of weeds, diseases, and pests (Miller et al., 2002; Tanaka et al., 2002), reduction in the risk of crop failure, farm inputs, and duration of fallow, and improvement in economic and environmental sustainability (Matson et al., 1997; Gregory et al., 2002).

Stacked crop rotations where same crop types are grown successively for several years in the rotation have been used to manage weeds and pests compared with alternate-year rotation (Garrison et al., 2014, Nickel, 2014). Stacked rotation favors weeds for increased competition with each other in similar environments for a longer period of time, allows the same herbicide to use in the successive year that can effectively control weeds (Garrison et al., 2014), and inhibits weeds and insects from building resistance to herbicides and pesticides through increased diversity (Nickel, 2014). Another practice to control weeds and pests is to alter cultural practice. Practices that use higher crop seeding rates, banded fertilization, and delayed planting and harvest have been effective in controlling weeds compared with recommended seeding rates, broadcast fertilization, and early planting and harvest (Strydhorst et al., 2008; Nichols et al., 2015). Higher seeding rate increases competition of crops with weeds, banded fertilization in rows beneath crop seeds reduces nutrient availability to weeds, and delayed planting after late application of pre-plant herbicide kills weed seedlings, all of which can effectively control weeds (Strydhorst et al., 2008; Nichols et al., 2015). Tall stubble increases soil water content by catching more snow than short stubble and also reduces light penetration in the ground which reduces weed growth (Strydhorst et al., 2008; Nichols et al., 2015).

Our objectives were to: (i) quantify the effect of crop rotations (stacked and alternate-year rotations and continuous monocropping) and cultural practices (traditional and ecological) on the amount of crop biomass (stems and leaves) residue returned to the soil, grain yield, and STC at the 0- to 125-cm depth from 2005 to 2011 in eastern Montana, and (ii) identify management practices that increase soil C storage and dryland crop yields. We hypothesized that stacked crop rotation and the ecological cultural practice would maintain or increase dryland soil C storage and annualized crop yield compared with alternate-year rotation or continuous monocropping and the traditional cultural practice.

MATERIALS AND METHODS

Site and Treatments

The experiment was conducted from 2005 to 2011 at the USDA Conservation District Farm, 11 km north of Culbertson, MT. The soil was a Williams loam (fine-loamy, mixed, superactive, frigid, Typic Argiustoll) with 2% slope. At the initiation of the experiment in April 2005, the soil at the 0- to 15-cm depth had 660 g kg^{-1} sand, 180 g kg^{-1} silt, 160 g kg^{-1} clay, 10.1 g kg^{-1} SOC (or 19.3 Mg C ha^{-1}), 7.2 pH, and 1.27 Mg m^{-3} bulk density. The site has mean (115-yr average) monthly air temperature ranging from −8°C in January to 23°C in July and August and a mean annual precipitation of 341 mm, 70% of which occurs during the growing season (April–August). Cropping history for 12 yr prior to the experiment initiation was continuous durum under conventional tillage.

Treatments included 4-yr rotations of two stacked and two alternate-year crop rotations along with a continuous monocropping, each with two cultural practices. Stacked rotations included durum-durum-canola-pea (D–D–C–P) and durum-durum-flax-pea (D–D–F–P). Alternate-year rotations included durum-canola-durum-pea (D–C–D–P) and durum–flax–durum-–pea (D–F–D–P). Monocropping included CD for comparison with other crop rotations. Each phase of the crop rotation was present in every year. Cultural practices were traditional and ecological practices that included combinations of various tillage practices, seed rates, N fertilization rates and methods, and stubble heights at crop harvest for durum, pea, canola, and flax (Table 1). For example, durum in the traditional practice was planted under conventional till with 1,008, 000 seeds ha^{-1}, broadcast N fertilization, and 19 cm stubble height. In the ecological practice, durum was planted under no-till with 1,344, 000 seeds ha^{-1}, banded N fertilization, and 33 cm stubble height. Stubble height for pea, canola, and flax, however, was 2 cm above the ground. Plots in the conventional-till treatment (traditional practice) were tilled in the spring before crop planting with a field cultivator to a depth of 7 to 8 cm for seedbed preparation and weed control. In the no-till treatment, plots were left undisturbed, except during planting and fertilization in rows. Because most of the management practices used in the ecological treatment are effective in controlling weeds compared with the traditional treatment (Strydhorst et al., 2008; Nichols et al., 2015), we expected that the ecological practice would be more effective in enhancing crop yields and STC by controlling weeds than the traditional practice. Cultural practice as the main plot and crop rotation as the split-plot treatment were arranged in a randomized complete block design with three replications. Plot size was 36 by 12 m.

Crop Management

In each year, 2005 to 2011, canola and pea were planted in early April, durum in late April, and flax in late April to early May. All crops were planted with a no-till drill equipped with low-disturbance Barton double-shoot disk openers on 20-cm centers. At planting, N fertilizer was applied at different rates

Table 1. Description of cultural practices (traditional and ecological) used for crops in the rotation.

Crop	Cultural practice	Tillage	Seed rate	N fertilization rate	Method of N fertilization	P fertilization rate	K fertilization rate	Durum stubble height
			kg ha^{-1}	kg N ha^{-1}		kg P ha^{-1}	kg K ha^{-1}	cm
Durum	Traditional	Conventional till	1,008,000†	127	Broadcast	29	27	19
	Ecological	No till	1,344,000†	127	Banded	29	27	33
Pea	Traditional	Conventional till	101	6	Broadcast	29	27	2
	Ecological	No till	140	6	Banded	29	27	2
Canola	Traditional	Conventional till	6	94	Broadcast	29	27	2
	Ecological	No till	9	94	Banded	29	27	2
Flax	Traditional	Conventional till	34	58	Broadcast	29	27	2
	Ecological	No till	50	58	Banded	29	27	2

† Number of seeds ha^{-1}.

to various crops (Table 1) from urea (46% N) and monoammonium phosphate (11% N, 23% P). In addition, canola received N fertilizer from ammonium sulfate (21% N, 24% S), which also supplied 24 kg S ha^{-1}. Pea received N from monoammonium phosphate while applying as a P fertilizer. Nitrogen rates were based on yield goals of 1400 kg ha^{-1} for canola, 1075 kg ha^{-1} for flax, and 1613 kg ha–^{1} for durum. Nitrogen rates were adjusted by deducting soil NO_3–N content to a depth of 60 cm measured in the autumn of the previous year from desired N rates. Nitrogen fertilizers were broadcast and incorporated to a depth of 8 cm during tillage in the traditional cultural practice. In the ecological practice, N fertilizers were banded to a depth of 5 cm below and 5 cm to the side of the seed. Phosphorus from monoammnium phosphate and K from muriate of potash (52% K) were banded to all crops at planting in all treatments. Growing season weeds were controlled with selective post emergence herbicides appropriate for each crop. Contact herbicides were applied at postharvest and pre-planting.

In late July and August of each year, aboveground total biomass (grains, stems, and leaves) yield of durum, pea, canola, and flax was determined by collecting biomass from two 0.5 m^2 areas outside yield rows in all plots, oven-drying at 55°C for 7 d, and weighing. All plants were cut by hand at a height of 2 cm above the ground for total biomass sampling. Grain yield was determined by harvesting grains from an area of 6 by 34 m from central rows of the plot using a combine harvester, oven-drying at 55°C for 7 d, and weighing. Biomass (stems and leaves) yield was determined by deducting grain yield from total biomass yield. After grain harvest, biomass residue of all crops was returned to the soil. Because stubble height treatment was used only for durum and not to other crops, it was assumed that durum harvested at 2 cm above the ground from a small area (1 m^2) for total biomass determination will not severely impact the effect of different stubble heights (Table 1) on crop yields and STC.

Soil Sample Collection and Analysis

In April 2005, October 2008, and October 2011, soil samples were collected with a truck-mounted hydraulic probe (3.5 cm i.d.) from the 0- to 125-cm depth from five places in the central rows of each plot, separated into 0- to 5-, 5- to 10-, 10- to 20-, 20- to 50-, 50- to 88-, and 88- to 125-cm depth increments, and composited within a depth (five composite samples per treatment of a replication per depth). Samples were air-dried, ground, and sieved to 2 mm for determining STC concentration. Coarse residue, roots, and gravel that did not pass through the sieve were discarded. Because of the incomplete amount of soils and their disturbance in each core due to the presence of hard layers at greater depths in some plots, these samples could not be used for determining the bulk density. As a result, bulk density was determined by collecting soil samples from a separate undisturbed core from each depth in each plot at the same time as above in every year. The core was oven-dried at 105°C for 24 h and weighed, from which the bulk density was determined by dividing the weight of the oven-dried soil by the volume of the core.

The STC concentration (g C kg^{-1} or mass/mass basis) in soil samples was determined by using a high induction furnace C and N analyzer (LECO Corp., St Joseph, MI) after grinding the samples to <0.5 mm. The STC content (Mg C ha^{-1} or mass/volume basis) at each depth interval was calculated by multiplying STC concentration by the bulk density and the thickness of the soil layer. The STC content at 0 to 125 cm was determined by summing the contents from individual soil layers.

Data Analysis

Data for crop biomass and grain yields and STC content at each depth were analyzed using the SAS-MIXED model (Littell et al., 2006). Crop rotation (split-plot treatment), cultural practice (main-plot treatment), and their interaction were considered as fixed effects, replication and cultural practice × replication as random effects, and year as the repeated measure variable. For soil bulk density and STC concentration, soil depth was considered as the split-split-plot treatment and another fixed effect and data were analyzed as above. Because each phase of the crop rotation was present in every year, data for phases were averaged within a rotation and the averaged value (annualized crop biomass and grain yields as well as STC concentration and content) was used for a rotation for the analysis. Means were separated by using the least square means test when treatments and interactions were significant (Littell et al., 2006). Linear regression analysis between STC concentration and year was conducted to determine soil C sequestration rate. For this, the timing of soil sampling, that is, April 2005, October 2008, and October 2011 were used as 0, 3.5, and 6.5 yr, respectively. Statistical significance was evaluated at $P \leq 0.05$, unless otherwise stated.

RESULTS AND DISCUSSION

Annualized Crop Biomass and Grain Yields

Annualized crop biomass (stems and leaves) yield varied with crop rotations and years, with significant interactions for crop rotation × year and cultural practice × year (Table 2). Biomass, averaged across cultural practices, was greater with D–C–D–P and D–D–C–P than other crops rotations in 2007 (Table 3). In 2008, biomass was greater with CD, D–C–D–P, and D–D–C–P than D–F–D–P. In 2010, biomass was greater with CD than D–D–C–P and D–F–D–P. Averaged across crop rotations, biomass was greater with the ecological than the traditional practice in 2007 and 2011. Averaged across cultural practices and years, biomass was greater with D–C–D–P and D–D–C–P than other crop rotations (Table 2). Averaged across treatments, biomass was greater in 2010 than other years.

Table 2. Effects of crop rotation and year on annualized crop biomass (stems and leaves) and grain yields.

Crop rotation†	Year	Annualized biomass yield	Annualized grain yield
		Mg ha^{-1}	
CD		3.32b‡	1.77a
D–C–D–P		4.02a	1.76a
D–D–C–P		3.90a	1.70a
D–F–D–P		3.39b	1.63ab
D–D–F–P		3.56b	1.54b
	2005	3.61c	1.93b
	2006	3.56c	0.97d
	2007	4.05b	1.41c
	2008	2.92d	1.49c
	2009	3.39c	1.94b
	2010	4.64a	2.22a
	2011	3.30c	1.78b
Significance			
Crop rotation (*R*)		***	*
Cultural practice (C)		ns§	ns
R × C		ns	ns
Year (Y)		***	***
R × Y		***	ns
C × Y		*	*
R × C × Y		ns	ns

* Significant at *P* = 0.05.

*** Significant at *P* = 0.001.

† Crop rotations are CD, continuous durum; D–C–D–P, durum–canola–durum–pea; D–D–C–P, durum–durum–-canola–pea; D–F–D–P, durum–flax–durum–pea; and D–D–F–P, durum–durum–flax–pea.

‡ Numbers followed by different letters within a column in a set are significantly different at *P* = 0.05 by the least square means test.

§ ns, not significant.

Enhanced biomass yield of canola, flax, and pea increased annualized biomass with D–C–D–P and D–D–C–P in 2007 and 2008 when growing season precipitation (April–August) was below the 115-yr average (Table 4). Below-average growing season precipitation (20–83 mm below the average) in June and July in these years, however, reduced durum growth which decreased annualized biomass with CD, D–F–D–P, and D–D–F–P. In contrast, above-average growing season precipitation (182 mm above the average) increased biomass with CD compared with D–D–C–P and D–F–D–P in 2010. Lower biomass yield with flax than other crops reduced biomass with D–F–D–P and D–D–F–P in most years. Reduced weed growth due to higher seed rate, enhanced N availability due to banded N fertilization, and increased soil water availability due to no-till likely increased biomass in the ecological than the traditional practice in 2007 and 2011. While higher seed rate reduces weed growth due to increased competition with crops (Strydhorst et al., 2008; Garrison et al., 2014), increased soil water conservation due to accumulation of residue at the soil surface increases crop yield with no-till compared with conventional till (Farahani et al., 1998; Halvorson et al., 1999). Biomass was similar between stacked and alternate-year crop rotations (Tables 2 and 3).

As with biomass yield, annualized crop grain yield varied with crop rotations and years, with a significant interaction for cultural practice × year (Table 2). Reduced weed growth due to increased seeding rates and increased N and water availability from delayed N fertilization, followed by increased soil water conservation as a result of no-till, likely increased grain yield in the ecological than the traditional practice during the above-average growing season precipitation in 2010 and

Table 3. Effects of crop rotation and cultural practice on annualized crop biomass (stems and leaves) and grain yields from 2005 to 2011.

Crop rotation†	Cultural practice‡	2005	2006	2007	2008	2009	2010	2011
		Annualized biomass yield, Mg ha^{-1}						
CD		3.23§	3.76	3.80b§	2.94a	2.93	5.53a	3.02
D–C–D–P		3.98	3.58	5.69a	3.46a	3.67	4.72ab	3.02
D–D–C–P		3.89	3.80	5.66a	3.03a	3.48	4.31b	3.13
D–F–D–P		3.56	3.33	3.57b	2.52b	3.29	4.09b	3.35
D–D–F–P		3.67	3.30	3.54b	2.61ab	3.55	4.55ab	3.98
	Traditional	3.63	3.74	3.78b	2.98	3.40	4.67	2.99b
	Ecological	3.94	3.37	4.33a	2.85	3.38	4.60	3.61a
		Annualized grain yield, Mg ha^{-1}						
	Traditional	1.86	0.99	1.39	1.58	1.85	2.04b	1.56b
	Ecological	2.06	0.94	1.44	1.40	2.02	2.41a	2.00a

† Crop rotations are CD, continuous durum; D–C–D–P, durum–canola–durum–pea; D–D–C–P, durum–durum–canola–pea; D–F–D–P, durum-flax-durum-pea; D–D–F–P, durum–durum–flax–pea.

‡ See Table 1 for the description of the cultural practice.

§ Numbers followed by different letters within a column in a set are significantly different at *P* = 0.05 by the least square means test.

2011 (Tables 3 and 4). Lower yield of flax than other crops reduced grain yield with D–D–F–P than CD, D–C–D–P, and D–D–C–P (Table 2). Above-average growing season precipitation increased both average biomass and grain yields across treatments in 2010 than other years (Tables 2 and 4). In contrast, biomass and grain yields were lower in 2006, 2007, and 2008 than other years due to below-average growing season precipitation. Differences in crop residue returned to the soil among treatments and years influenced STC at various depths, as described below.

Soil Bulk Density

Soil bulk density increased with depth, but was unaffected by treatments, years, and their interactions (Table 5). Averaged across treatments and years, bulk density increased from 1.12 Mg m^{-3} at 0 to 5 cm to 1.51 Mg m^{-3} at 88 to 125 cm. Presence of large amount of gravel and hard layers rich in calcite and dolomite at the subsurface layers increased bulk density with depth. High variability of soil mass in the core among plots may be a possible region for the nonsignificant effect of treatment and year in bulk density. Variation in bulk density among soil depths may affect STC content, as discussed below.

Soil Total Carbon

Soil total C concentration varied with crop rotations, years, and depths (Table 5). Interactions were significant for crop rotation × cultural practice, crop rotation × depth, crop rotation × cultural practice × depth, and year × depth.

The STC concentration decreased from 0 to 5 to 10 to 20 cm, increased at 50 to 88 cm, and then either remained at similar level or decreased with depth for all treatments (Tables 5 and 6). Averaged across years, STC concentration at 20 to 50 cm was greater with CD and D–F–D–P than other crop rotations in the traditional practice (Table 6). At 50 to 88 cm, STC concentration was greater with D–F–D–P than D–D–F–P. In the ecological practice, STC concentration at 20 to 55 cm was greater with D–C–D–P than other crop rotations. The STC concentration was also greater in the traditional than the ecological practice with CD at 5 to 10 and 20 to 50 cm and with D–F–D–P at 20 to 50 cm, but the trend reversed with D–C–D–P at 20 to 50 cm. Averaged across cultural practices and years, STC concentration at 20 to 50 cm was greater with CD, D–C–D–P, D–F–D–P, and D–D–C–P than D–D–F–P.

Decreased concentration of STC from 0 to 5 cm to 10 to 20 cm (Table 6) was probably due to reduction of both SOC and SIC with depth. The SOC decreases due to reduction

Table 5. Soil bulk density and total carbon (STC) concentration averaged across treatments and years as affected by depth.

Soil depth	Bulk density	STC concentration
	Mg m^{-3}	g C kg^{-1}
0–5 cm	1.12c†	15.8c
5–10 cm	1.32b	13.0d
10–20 cm	1.36b	10.9e
20–50 cm	1.44ab	17.0c
50–88 cm	1.47a	26.4a
88–125 cm	1.51a	23.6b
Significance		
Crop rotation (R)	ns‡	***
Cultural practice (C)	ns	ns
R × C	ns	*
Year (Y)	ns	***
R × Y	ns	ns
C × Y	ns	ns
R × C × Y	ns	ns
Soil depth (D)	***	***
R × D	ns	*
C × D	ns	ns
R × C × D	ns	*
Y × D	ns	*
R × Y × D	ns	ns
C × Y × D	ns	ns
R × C × Y× D	ns	ns

* Significant at $P = 0.05$.

*** Significant at $P = 0.001$.

† Numbers followed by different letters within a column in a set are significantly different at $P = 0.05$ by the least square means test.

‡ ns, not significant.

Table 4. Monthly total precipitation from 2005 to 2011 at the experimental site.

Month	2005	2006	2007	2008	2009	2010	2011	115-yr average
	mm							
January	11	3	3	1	8	5	2	9
February	1	1	5	6	2	2	4	5
March	12	13	19	12	3	4	7	14
April	0	80	21	12	53	33	35	22
May	79	44	128	43	24	118	172	51
June	172	55	49	58	27	69	71	71
July	42	30	21	29	100	125	42	68
August	29	36	8	21	96	83	25	34
September	36	67	19	62	23	23	17	29
October	26	10	9	40	69	32	16	22
November	19	1	0	40	1	22	2	11
December	9	0	0	13	1	7	4	10
April-August	321	244	226	163	300	428	345	246
January-December	434	339	283	336	406	522	397	341

Table 6. Soil total carbon (STC) concentration at various depths as influenced by crop rotation and cultural practice averaged across years.

Soil depth	STC with various crop rotations†				
	CD	D–C–D–P	D–D–C–P	D–F–D–P	D–D–F–P
	g kg^{-1}				
	Traditional practice‡				
0–5 cm	16.4c§	15.5b	15.7b	16.0c	16.1b
5–10 cm	14.0d	12.7c	12.7c	13.4d	13.8b
10–20 cm	11.6d	10.1c	10.4c	11.3d	11.0c
20–50 cm	20.5bA¶	16.2bB	14.9bB	18.6cA	15.9bB
50–88 cm	26.1aAB	26.6aAB	25.7aAB	27.7aA	25.2aB
88–125 cm	23.8a	24.5a	22.7b	23.5b	23.1a
	Ecological practice‡				
0–5 cm	15.9c	15.8d	15.5c	15.6b	15.7c
5–10 cm	12.5d	12.5e	12.9c	13.3bc	12.7d
10–20 cm	11.6d	10.7e	10.3d	11.3c	10.4d
20–50 cm	17.2cB	19.6cA	15.8cB	16.6bB	14.9cdB
50–88 cm	26.3a	27.2a	26.3a	26.6a	25.7a
88–125 cm	23.8b	24.0b	23.3b	24.8a	22.7b
	Averaged across cultural practices				
0–5 cm	16.1d	15.7d	15.6c	15.8c	15.9c
5–10 cm	13.2e	12.6e	12.8e	13.3d	13.3d
10–20 cm	11.6e	10.4f	10.3d	11.3d	10.7e
20–50 cm	18.8cA	17.9cA	15.4cB	17.6cA	15.4cB
50–88 cm	26.2a	26.9a	26.0a	27.2a	25.5a
88–125 cm	23.8b	24.3b	23.0b	24.1b	22.9b

† Crop rotations are CD, continuous durum; D–C–D–P, durum–canola–durum–pea; D–D–C–P, durum–durum–canola–pea; D–D–F–P, durum–durum–flax–pea, and D–F–D–P, durum–flax–durum–pea.

‡ See Table 1 for the description of the cultural practice.

§ Numbers followed by different lowercase letters within a column in a crop rotation and cultural practice are significantly different between soil depths at *P* = 0.05 by the least square means test.

¶ Numbers followed by different uppercase letters within a row in a cultural practice depth and a depth are significantly different between crop rotations at *P* = 0.05 by the least square means test.

in C inputs from crop residue and root (Sainju et al., 2015a). The SIC decreases in the surface layer due to dissolution of calcite and dolomite and their translocation from the surface to the subsurface layers as a result of soil acidification from continuous application of NH_4–based N fertilizer in the plow layer for crop production (Liebig et al., 2002; Mikhailova and Post, 2006). In a near-by experiment, Sainju et al. (2015b) reported that soil pH at the 0- to 7.5-cm depth decreased from 6.20 to 5.02 after 30 yr due to soil acidification as a result of continuous application of NH_4–based N fertilizers to crops. Other possible reasons for increased STC with depth could be enhancement of SIC due to upward capillary movement of groundwater rich in Ca and Mg during dry periods and parent material rich in calcite and dolomite (Aase and Pikul, 1995).

Greater crop residue returned to soil, followed by higher C/N ratio of durum residue than other crop residues, likely increased STC concentration at 20 to 50 and 50 to 88 cm with CD, D–C–D–P, and D–F–D–P compared with other crop rotations in traditional and ecological practices (Table 6). Crop biomass residue returned to the soil was greater with D–C–D–P than other crop rotations, except D–D–C–P (Tables 2 and 3). Increased crop residue returned to the soil can increase C input and therefore SOC (Kuo et al., 1997). Sainju et al. (2015a) also found greater SIC at 30 to 60 and 60 to 90 cm with continuous spring wheat than spring wheat–pea in a nearby long-term (30 yr) experiment due to increased amount of crop residue returned to the soil. In contrast, reduced decomposition of the residue due to higher C/N ratio of durum than other crops probably increased STC concentration with CD, as residues with higher C/N ratio decompose more slowly than residues with lower ratio (Kuo et al., 1997). Assuming that crop residues contain 400 g C kg^{-1} in general, the average C/N ratios of biomass residues for durum, canola, flax, and pea with N concentrations 16, 20, 22, and 25 g N kg^{-1} across treatments and years in this experiment were 25, 20, 18, and 16, respectively. Similar results have been reported by various researchers (Campbell et al., 2002; Halvorson et al., 2002; Sherrod et al., 2003; Sainju et al., 2014, 2015a).

The greater STC concentration in the traditional than the ecological practice with CD at 5 to 10 and 20 to 50 cm and with D–F–D–P at 20 to 50 cm was probably a result of increased SIC and SOC concentrations due to residue incorporation into the soil due to tillage. Sainju et al. (2015a) in a nearby long-term (30 yr) experiment found that SOC increased with conventional tillage compared with no-tillage due to residue incorporation as a result of tillage. Similarly, several researchers (Cihacek and Ulmer, 2002; Monger, 2002; Sainju et al., 2015a) found greater SIC with conventional tillage than no-tillage due to residue incorporation into the soil. In contrast, greater STC concentration in the ecological than the traditional practice with D–C–D–P at 20 to 50 cm was probably a result of enhanced root growth due to increased soil water conservation due to no-tillage (Sainju et al., 2005). Because annualized crop biomass and grain yields were greater in the ecological than the traditional practice in most years (Table 3), it is likely that increased total aboveground biomass also increased belowground biomass in the ecological practice. Furthermore, soil bulk density was not different among treatments (Table 5), which indicates that no-tillage in the ecological practice did not significantly compact soil compared with conventional tillage in the traditional practice. Several researchers (Merrill et al., 1996; Rasse and Smucker, 1996). have reported greater root length density in wheat (*T. aestivum* L) and corn (*Zea mays* L.) in no-tillage than conventional tillage due to superior soil water conservation and cooler soil temperature that promoted root growth during the growing season in the summer.

The STC concentration at 0 to 5, 5 to 10, and 10 to 20 cm decreased with year, regardless of treatments (Fig. 1). The STC concentration declined at 0.03 g C kg^{-1} yr^{-1} at 0 to 5 cm to 0.39 g C kg^{-1} yr^{-1} at 5 to 10 cm. The STC concentration also declined at other depths, but the regression equations were not significant. The reduction in STC concentration with year could be a result of lower crop biomass production in semiarid dryland conditions because of limited precipitation and a shorter growing season than humid regions (Halvorson et al., 2002; Sherrod et al., 2003; Sainju et al., 2015a). A solution for maintaining or increasing STC would be to plant perennial crops, such as perennial grasses, which have higher root biomass yield than annual crops, where soil is left in undisturbed condition for longer periods, and plant residue is continuously recycled throughout the year (Sainju and Lenssen, 2011).

The STC content at 0 to 125 cm varied among crop rotations, but the effects of cultural practice, year, and their interactions were not significant (Table 7). The STC content was lower with D–D–F–P than other crop rotations. Although STC content was lower with D–D–C–P, it was not significantly different from D–C–D–P.

The lower STC content at 0 to 125 cm with D–D–F–P than other crop rotations was probably a result of reduced crop biomass residue returned to the soil (Table 2), followed by decreased STC concentrations at most depths (Table 6). Similarly, the lower STC content at 0 to 125 cm with stacked than alternate-year crop rotations (D–D–C-P vs. D–C–D–P and D–D–F–P vs. D–F–D–P) could be a result of differences in sequence of crops with residues of various C/N ratios in the rotation. It is likely that the return of durum residue with higher C/N ratio continuously for 2 yr to the soil increased STC in the beginning, but STC declined in subsequent years as durum residue decomposed and residues with lower C/N ratios (pea, canola, and flax) were added in the last 2 yr of the 4-yr stacked rotation. Plaza-Bonilla et al. (2016) reported that SOC continually decreased when the frequency of legumes with lower C/N ratio in rotation with durum increased compared to continuous durum with higher C/N ratio. In the alternate-year rotation, STC levels may have been maintained or increased by alternating the supply of residues from crops with higher and lower C/N ratios in succeeding years. In

Table 7. Soil total carbon (STC) content at the 0–125 cm profile as affected by crop rotation.

Crop rotation†	STC at 0–125 cm
	Mg C ha^{-1}
CD	394.6a‡
D–C–D–P	395.4a
D–D–C–P	387.1a
D–F–D–P	395.4a
D–D–F–P	370.2b
Significance	
Crop rotation (R)	**
Cultural practice (C)	ns§
R × C	ns
Year (Y)	ns
R × Y	ns
C × Y	ns
R × C × Y	ns

** Significant at *P* = 0.01.

† Crop rotations are CD, continuous durum; D–C–D–P, durum–canola–durum–pea; D–D–C–P, durum–durum–canola–pea; D–F–D–P, durum–flax–durum–pea; and D–D–F–P, durum–durum–flax–pea.

‡ Numbers followed by different letters within a column are significantly different at *P* = 0.05 by the least square means test.

§ ns, not significant.

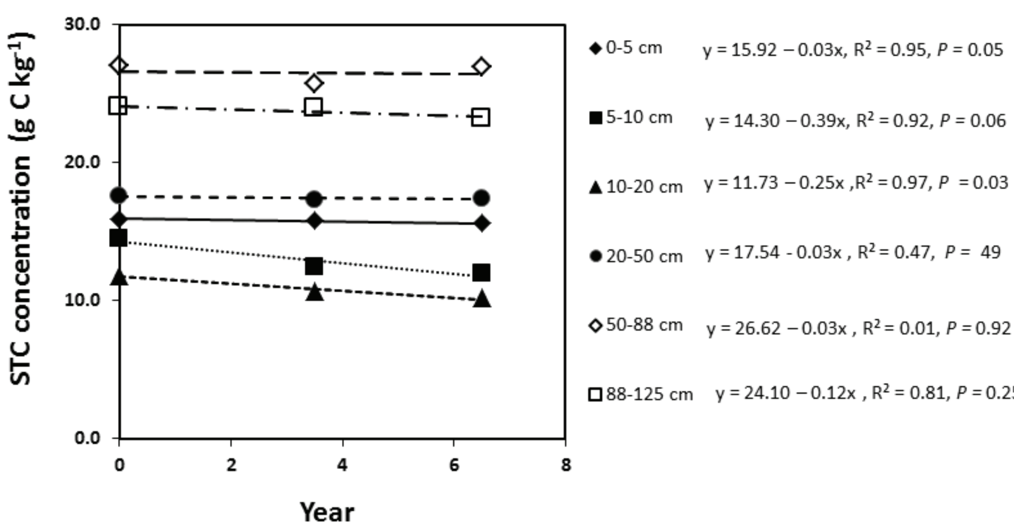

Fig. 1. Relationship between soil total C concentration at various soil depths and year averaged across treatments. Year 0, 3.5, and 6.5 represent the time of soil sampling in April 2005, October 2008, and October 2011, respectively.

other words, decreased STC content with rapid decomposing residue due to lower C/N ratio may have been compensated by increased STC content with slow decomposing residue due to higher C/N ratio, thereby stabilizing STC levels, when crops with higher and lower C/N ratios were subsequently grown in the alternate-year rotation.

Nonsignificant differences in STC content at 0 to 125 cm among CD, D–C–D–P, and D–F–D–P (Table 7) suggests that alternate-year crop rotation with diversified crops of cereals, legumes, and oilseeds can be equally effective in storing C in the soil as continuous cereal monocropping. As alternate-year crop rotation can also effectively control weeds and pests compared with monocropping (Miller et al., 2002; Tanaka et al., 2002), alternate-year rotation with diversified crops may be used to sequester soil C, reduce C pollution in the terrestrial ecosystem, enhance soil health and quality, reduce farm inputs, and claim C credit compared with stacked rotation or continuous monocropping in dryland cropping systems.

CONCLUSIONS

Alternate-year crop rotations with cereals, legumes, and oilseed crops were effective in maintaining dryland STC levels and annualized grain yields similar to those in continuous cereal monocropping. Stacked crop rotation, especially D–D–F–P, reduced STC concentration in the subsurface layers, STC content in the whole soil profile, and grain yield compared with alternate-year rotation and monocropping by reducing crop biomass residue returned to the soil and by changing the sequence of residues with different C/N ratios in various years. Cultural practice interacted with crop rotation on STC concentration and crop yield, but had minimum effect on soil profile STC content. Soil total C concentration at 0 to 20 cm declined from 2005 to 2011, regardless of treatments. Stacked crop rotation, although may be beneficial in controlling weeds and pests, does not favor soil C storage and crop yield compared with alternate-year rotation. Alternate-year rotation, which may also reduce the infestations of weeds, diseases, and insects, can sustain soil C storage and crop yields compared with continuous cereal monocropping. As a result, alternate-year rotation may be used to reduce atmospheric C pollution, enhance soil health and quality, reduce farm inputs, and claim C credit in dryland cropping systems.

REFERENCES

Aase, J.K., and J.L. Pikul, Jr. 1995. Crop and soil response to long-term tillage practices in the northern Great Plains. Agron. J. 87:652–656. doi:10.2134/agronj1995.00021962008700040008x

Bauer, A., and A.L. Black. 1994. Quantification of the effect of soil organic matter content on soil productivity. Soil Sci. Soc. Am. J. 58:185–193. doi:10.2136/sssaj1994.03615995005800010027x

Black, A.L., and D.L. Tanaka. 1997. A conservation tillage cropping system study in the northern Great Plains of the United States. In: E.A. Paul, editor, Soil organic matter in temperate agroecosystems: Long-term experiments in North America. CRC Press, Boca Raton, FL. p. 335–342.

Bowman, R.A., M.F. Vigil, D.C. Nielsen, and R.L. Anderson. 1999. Soil organic matter changes in intensively cropped dryland systems. Soil Sci. Soc. Am. J. 63:186–191. doi:10.2136/sssaj1999.03615995006300010026x

Campbell, C.A., B.G. McConkey, S. Gameda, R.C. Izaurralde, B.C. Liang, R.P. Zentner, and D. Sabiurin. 2002. Efficiencies of conversion of residue C to soil C. In: L.M. Kimble, R. Lal, and R.F. Follett, editors, Agricultural practices and policies for carbon sequestration in soil. Lewis Publishers, Boca Raton, FL.. p. 305–314. doi:10.1201/9781420032291.ch29

Cihacek, L.J., and M.G. Ulmer. 2002. Effect of tillage on inorganic carbon storage in soils of the northern Great Plains of the U.S. In: L.M. Kimble, R. Lal, and R.F. Follett, editors, Agricultural practices and policies for carbon sequestration in soil. Lewis Publ., Boca Raton, FL. p. 63–69. doi:10.1201/9781420032291.ch6

Farahani, H.J., G.A. Peterson, and D.G. Westfall. 1998. Dryland cropping intensification: A fundamental solution to the efficient use of precipitation. Adv. Agron. 64:197–223. doi:10.1016/S0065-2113(08)60505-2

Gan, Y., C. Liang, C.A. Campbell, R.P. Zentner, R.L. Lemke, H. Wang, and C. Yang. 2012. Carbon footprint of spring wheat in response to fallow frequency and soil carbon changes over 25 years on the semiarid Canadian prairie. Eur. J. Agron. 43:175–184. doi:10.1016/j.eja.2012.07.004

Gan, Y., C. Liang, G. Huang, S.S. Malhi, S.A. Brandt, and F. Katepa-Mupondwa. 2011. Carbon footprint of canola and mustard is a function of the rate of N fertilizer. Int. J. Life Cycle Assess. 17:58–68. doi:10.1007/s11367-011-0337-z

Garrison, A.J., A.D. Miller, M.J. Ryan, S.H. Roxbourgh, and K. Shea. 2014. Stacked crop rotations exploit weed-weed competition for sustainable weed management. Weed Sci. 62:166–176. doi:10.1614/WS-D-13-00037.1

Gregory, P.J., J.S.I. Ingram, R. Anderson, R.A. Betts, V. Brovkin, T.N. Chase et al. 2002. Environmental consequences of alternative practices for intensifying crop production. Agric. Ecosyst. Environ. 88:279–290. doi:10.1016/S0167-8809(01)00263-8

Halvorson, A.D., A.L. Black, J.M. Krupinsky, and S.D. Merrill. 1999. Dryland winter wheat response to tillage and nitrogen within an annual cropping system. Agron. J. 91:702–707. doi:10.2134/agronj1999.914702x

Halvorson, A.D., B.J. Wienhold, and A.L. Black. 2002. Tillage, nitrogen, and cropping system effects on soil carbon sequestration. Soil Sci. Soc. Am. J. 66:906–912. doi:10.2136/sssaj2002.9060

Kuo, S., U.M. Sainju, and E.J. Jellum. 1997. Winter cover crop effects on soil organic carbon and carbohydrate. Soil Sci. Soc. Am. J. 61:145–152. doi:10.2136/sssaj1997.03615995006100010022x

Lal, R., R.F. Follett, and J. Kimble. 1999. Managing U.S. cropland to sequester carbon in soil. J. Soil Water Conserv. 53:374–381.

Liebig, M.A., G.E. Varvel, J.W. Doran, and B.J. Wienhold. 2002. Crop sequence and nitrogen fertilization effects on soil properties in the western Corn Belt. Soil Sci. Soc. Am. J. 66:596–601. doi:10.2136/sssaj2002.5960

Littell, R.C., G.A. Milliken, W.W. Stroup, R.D. Wolfinger, and O. Schabenberger. 2006. SAS for mixed models. SAS Inst. , Cary, NC.

Matson, P.A., W.J. Parton, A.G. Power, and M.J. Swift. 1997. Agricultural intensification and ecosystem properties. Science (Washington, DC) 277:504–509.

Merrill, S.D., A.L. Black, and A. Bauer. 1996. Conservation tillage affects root growth of dryland spring wheat under drought. Soil Sci. Soc. Am. J. 60:575–583. doi:10.2136/sssaj1996.03615995006000020034x

Mikhailova, E.A., and C.J. Post. 2006. Effects of land use on soil inorganic carbon stocks in the Russian Chernozem. J. Environ. Qual. 35:1384–1388. doi:10.2134/jeq2005.0151

Miller, P.R., B. McConkey, G.W. Clayton, S.A. Brandt, J.A. Staricka, A.M. Johnston et al. 2002. Pulse crop adaptation in the northern Great Plains. Agron. J. 94:261–272. doi:10.2134/agronj2002.0261

Monger, C.H. 2002. Pedogenic carbonate: Linked between biotic and abiotic $CaCO_3$. In: Proceedings 17th World Congress of Soil Science, Bangkok, Thailand. 14–21 Aug. 2002. p. 897-1 to 897-9.

Mosier, A.R., A.D. Halvorson, C.A. Reule, and X.J. Liu. 2006. Net global warming potential and greenhouse gas intensity in irrigated cropping systems in northeastern Colorado. J. Environ. Qual. 35:1584–1598. doi:10.2134/jeq2005.0232

Nichols, V., N. Verhulst, R. Cox, and B. Govaerts. 2015. Weed dynamics and conservation agriculture principles: A review. Field Crops Res. 183:56–68. doi:10.1016/j.fcr.2015.07.012

Nickel, R. 2014. Stacking crop rotation controls pests. meredithagrimedia. http://www.agriculture.com/crops/corn/production/stacking-crop-rotation-controls-pests_137-ar45188 (accessed 23 Feb. 2016).

Paustian, K., O. Andren, H.H. Janzen, R. Lal, P. Smith, G. Tian et al. 1997. Agricultural soils as a sink to mitigate CO_2 emissions. Soil Use Manage. 13:230–244. doi:10.1111/j.1475-2743.1997.tb00594.x

Peterson, G.A., A.D. Halvorson, J.L. Havlin, O.R. Jones, D.G. Lyon, and D.L. Tanaka. 1998. Reduced tillage and increasing cropping intensity in the Great Plains conserve soil carbon. Soil Tillage Res. 47:207–218. doi:10.1016/S0167-1987(98)00107-X

Plaza-Bonilla, D., J.M. Nolot, S. Passot, and D. Raffaillac. 2016. Grain legume-based rotations managed under conventional tillage need cover crops to mitigate soil organic matter losses. Soil Tillage Res. 156:33–43. doi:10.1016/j.still.2015.09.021

Rasse, D., and A.M. Smucker. 1996. Tillage modifications of root growth, soil water, and nitrate contents in a corn-alfalfa succession. 5th Symposum International Society Root Research, Clemson, SC. 14–18 July 1996. p. 161.

Sainju, U.M. 2014. Cropping sequence and nitrogen fertilization impact on surface residue, soil carbon sequestration, and crop yields. Agron. J. 106:1231–1242. doi:10.2134/agronj14.0026

Sainju, U.M., B.L. Allen, T. Caesar-TonThat, and A.W. Lenssen. 2015a. Dryland soil carbon and nitrogen after thirty years of tillage and cropping sequence. Agron. J. 107:1822–1830. doi:10.2134/agronj15.0106

Sainju, U.M., B.L. Allen, T. Caesar-TonThat, and A.W. Lenssen. 2015b. Dryland soil chemical properties and crop yields affected by long-term tillage and cropping sequence. Springerplus 4:320. doi:10.1186/s40064-015-1122-4

Sainju, U.M., and A.W. Lenssen. 2011. Dryland soil carbon dynamics under alfalfa and durum-forage cropping sequences. Soil Tillage Res. 113:30–37. doi:10.1016/j.still.2011.02.002

Sainju, U.M., W.B. Stevens, and T. Caesar-Tonthat. 2014. Soil carbon and crop yields affected by irrigation, tillage, crop rotation, and nitrogen fertilization. Soil Sci. Soc. Am. J. 78:936–948. doi:10.2136/sssaj2013.12.0514

Sainju, U.M., W.F. Whitehead, and B.P. Singh. 2005. Tillage, cover crops, and nitrogen fertilization effects on cotton and sorghum root biomass, carbon, and nitrogen. Agron. J. 97:1279–1290. doi:10.2134/agronj2004.0213

Schomberg, H.H., and O.R. Jones. 1999. Carbon and nitrogen conservation in dryland tillage and cropping systems. Soil Sci. Soc. Am. J. 63:1359–1366. doi:10.2136/sssaj1999.6351359x

Sherrod, L.A., G.A. Peterson, D.G. Westfall, and L.R. Ahuja. 2003. Cropping intensity enhances soil organic carbon and nitrogen in a no-till agroecosystem. Soil Sci. Soc. Am. J. 67:1533–1543. doi:10.2136/sssaj2003.1533

Strydhorst, S.M., J.R. King, K.H. Lopetinsky, and K.N. Harker. 2008. Weed interference, pulse species, and plant density effects on rotational benefits. Weed Sci. 56:249–258. doi:10.1614/WS-07-118.1

Tanaka, D.L., J.M. Krupinsky, M.A. Liebig, S.D. Merrill, R.E. Ries, J.R. Hendrickson et al. 2002. Dynamic cropping systems: An adaptable approach to crop production in the northern Great Plains. Agron. J. 94:957–961. doi:10.2134/agronj2002.0957

West, T.O., and W.M. Post. 2002. Soil organic carbon sequestration rates by tillage and crop rotation: A global data analysis. Soil Sci. Soc. Am. J. 66:1930–1946. doi:10.2136/sssaj2002.1930